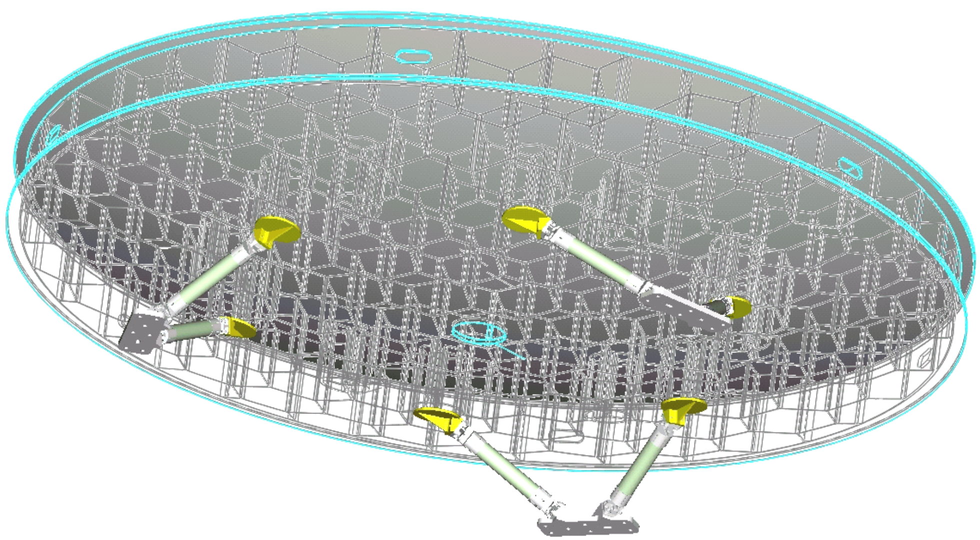
KEPLER PHOTOMETER
Primary Mirror Assembly
FEA Prediction and Measured Cryo Figure



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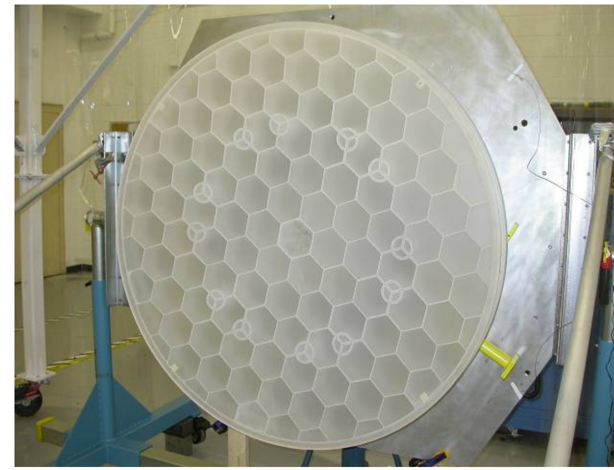
Overview

Accurately predicting optical figure at cyrogenic temperatures is difficult due to the following challenges:

- Must quantify variations in material properties, including spatial distribution
- Comprehensive material testing can aid in understanding adhesive behavior, but it remains difficult to accurately implement measured data
- FEA modeling needs to be cost effective and accurate, thus requiring a balance in model refinement

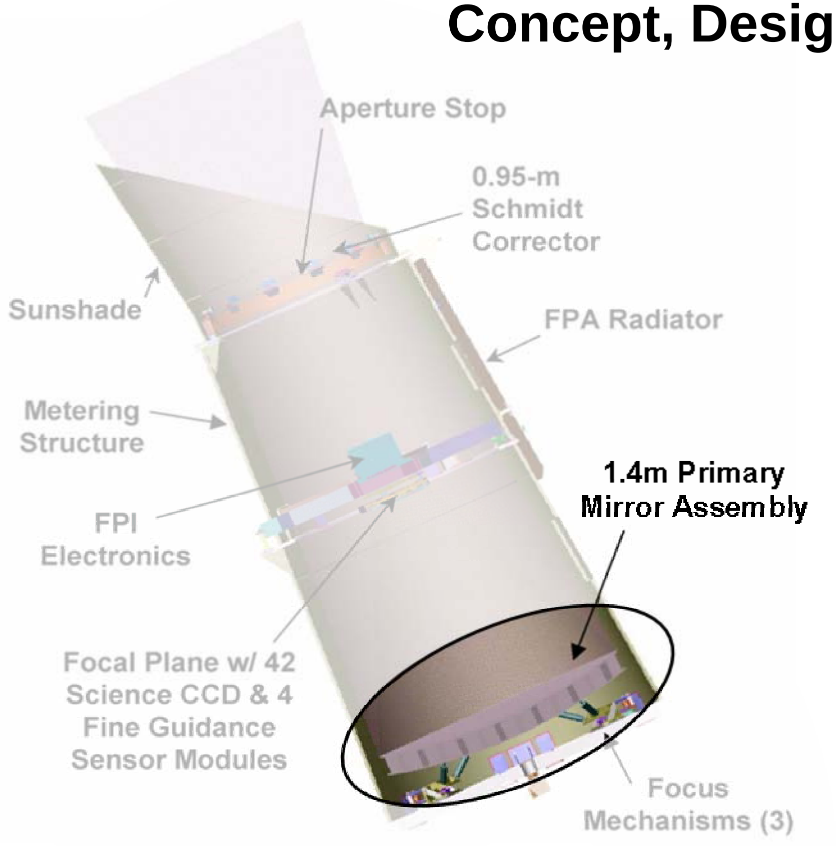


This presentation discusses cost effective methods used by L-3 Brashear to predict the Kepler PMA final cryo figure at -60 °C within 8% of the measured figure.

Kepler

L-3 Communications Brashear Role on Kepler

Responsible for Primary Mirror Assembly: Concept, Design, Fabrication, and Testing



- Design of 1.4m CA, lightweight, ULE, frit-bonded mirror – includes reinforced primary and alternate bonding sites
- Design and analysis of hexapod support structure – carbon fiber struts with titanium cross flexures
- PMA material selection & characterization
- PMA FEA analysis and figure predictions
- Strut fabrication and bond pad installation using space qualified procedures
- Strongback support fixture, mirror handling, and related tooling
- Mirror generation, metrology, PMA vibration and environmental testing
- Mirror coating

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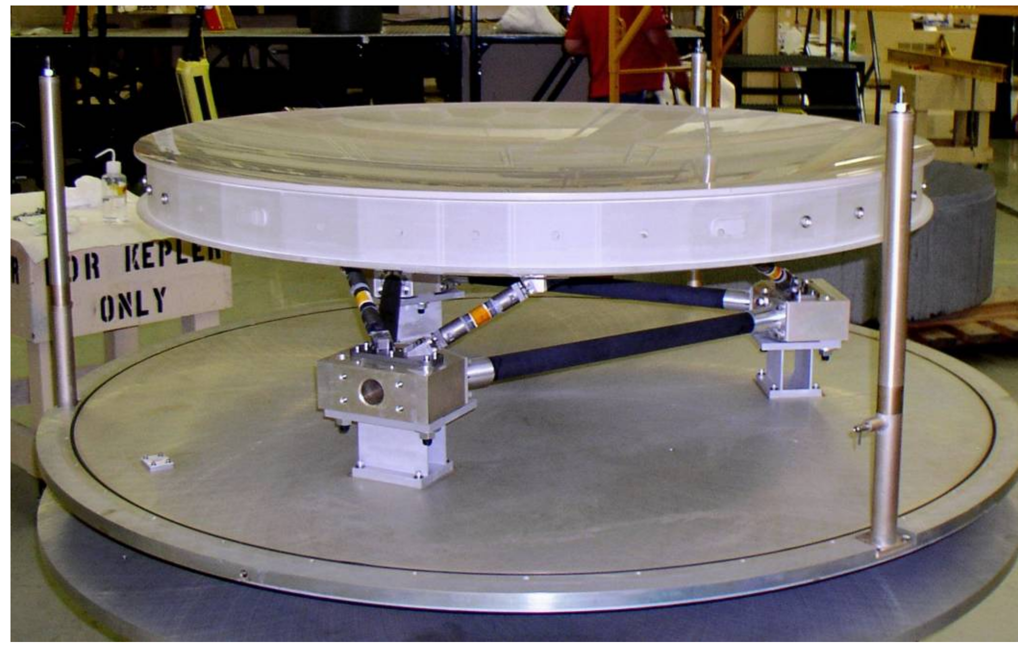
Key Features Which Make Kepler PMA Unique

- Systems approach to Primary Mirror Assembly design
- Accommodating broad operating temperature range and high stiffness
- Including alternate support attachment locations
- Integral design features to accommodate lifting, handling, tooling, metrology & coating

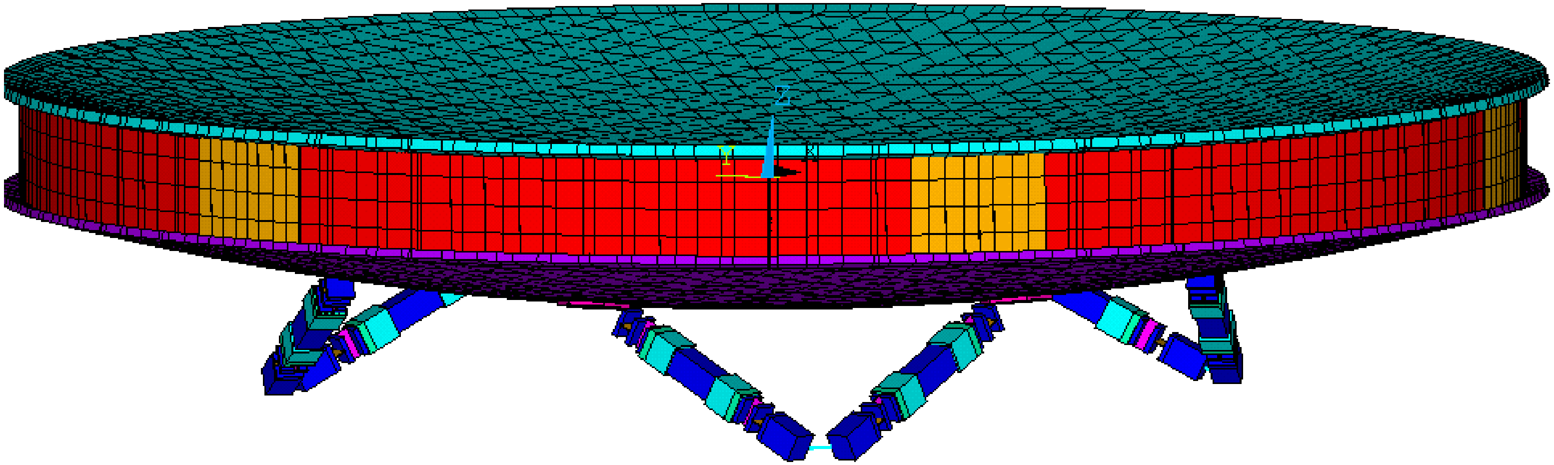


Kepler

Summary of FEA Models

Global PMA Model

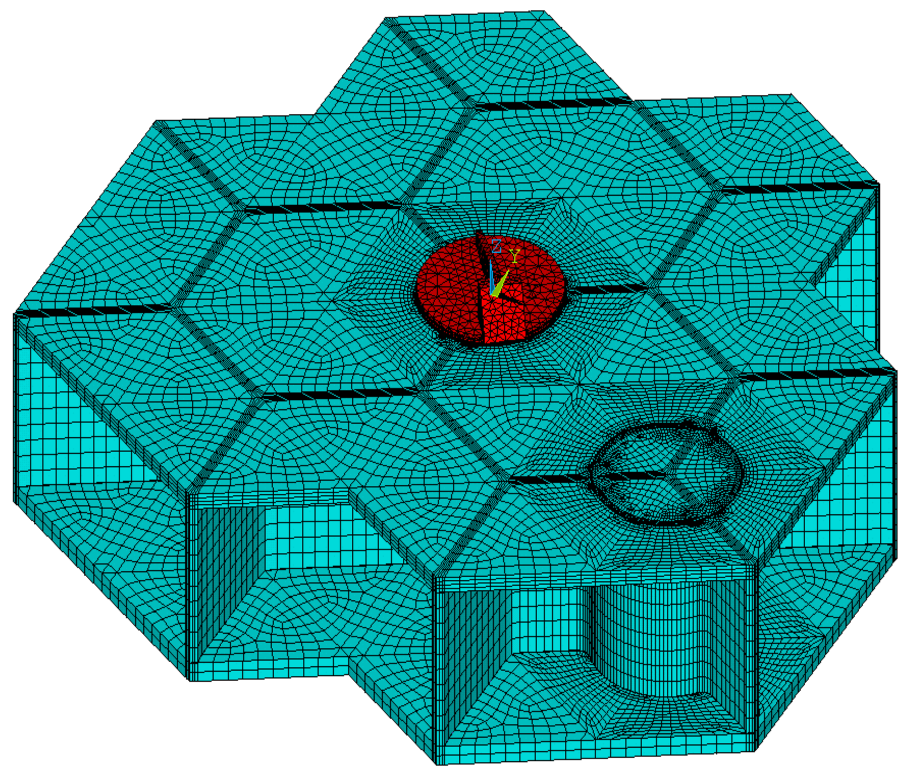
- Coarse mesh of full mirror with supports
- Limited elements for bond pad and adhesive
- Valid for stiffness estimation and global support displacements
- Used to calculate mechanical loads
- Used for figure predictions



Summary of FEA Models

Detailed PMA Model

- Planar representation of mirror structure around one bond pad without strut
- Accurate representation of bond pad and adhesive joint
- Provides high accuracy required for stress evaluation and local figure predictions
- A symmetric 60° slice of PM would have been more appropriate



Keys to Accurate Cryo Predictions

Material Characterization

How much do material properties deviate from nominal values?

- Characterized ULE boule CTE variations for facesheet, backsheet, and core
- Measured Invar CTE resulting from the applied heat treatment
- Measured adhesive stiffness and CTE, strain rate dependent

FEA Model Accuracy

Is the FEA model sufficiently detailed and refined?

- Global model is not sufficiently refined to accurately predict magnitude of local deformations around bond pad. Use detailed model to correlate global model.
- Performed analysis with measured component thicknesses (facesheet and backsheet) rather than nominal design values

Material Characterization

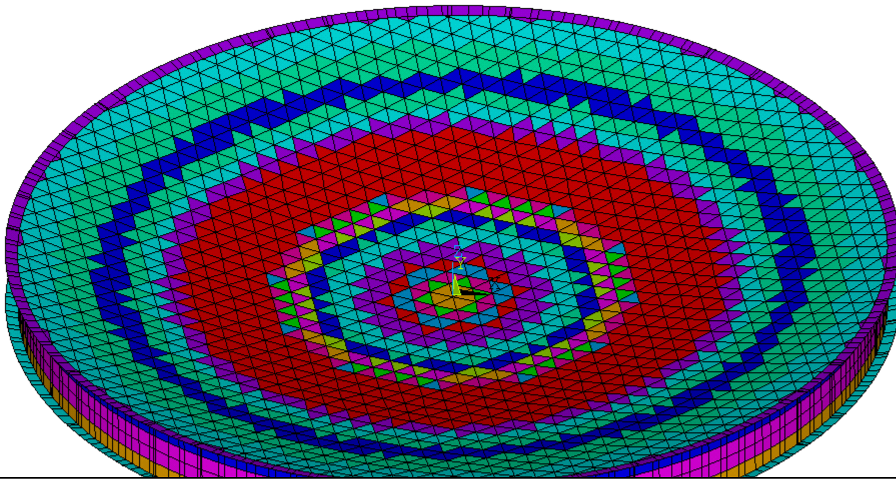
ULE CTE Mapping

- ULE nominal CTE applied using polynomial curve from Corning
- Facesheet and backsheet CTE variation mapped along 6 radial lines
- Core CTE variation mapped as function of height at 6 points
- CTE in each element is interpolated based on position, both radius and height in core

Lessons Learned:

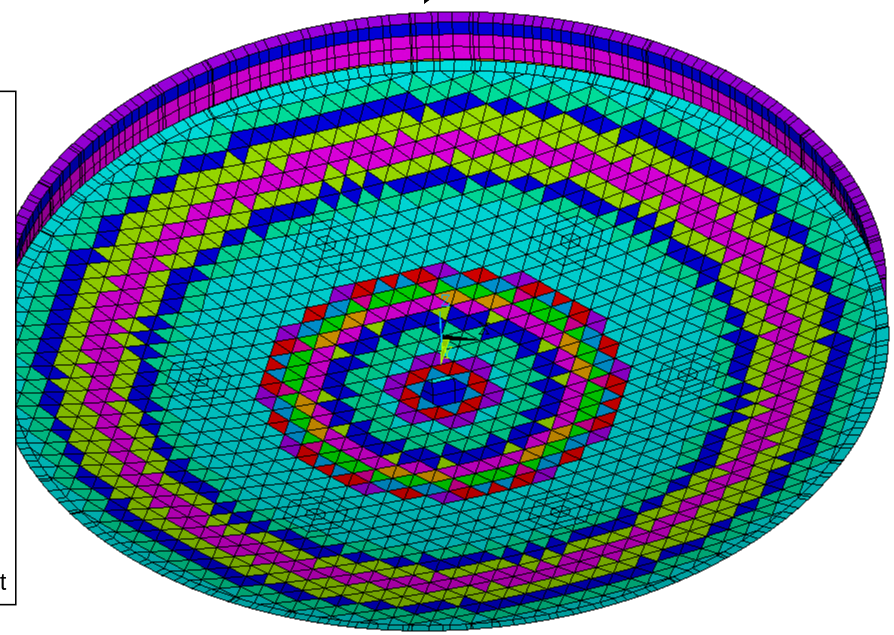
- CTE distribution shown to be rotationally symmetric, so core samples should have been chosen radially rather than circumferentially
- Given steep variations in CTE, a finer mesh in the global model would allow smoother interpolation

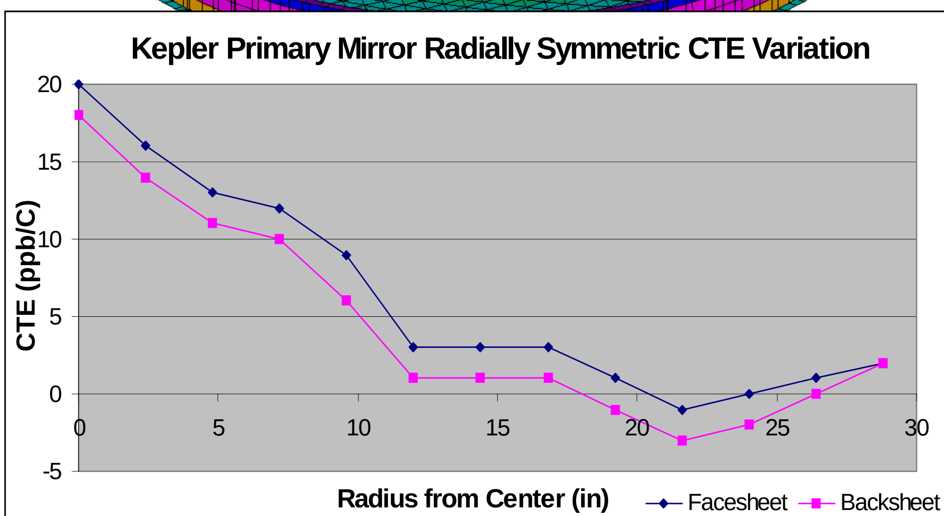
Kepler Primary Mirror CTE Mapping



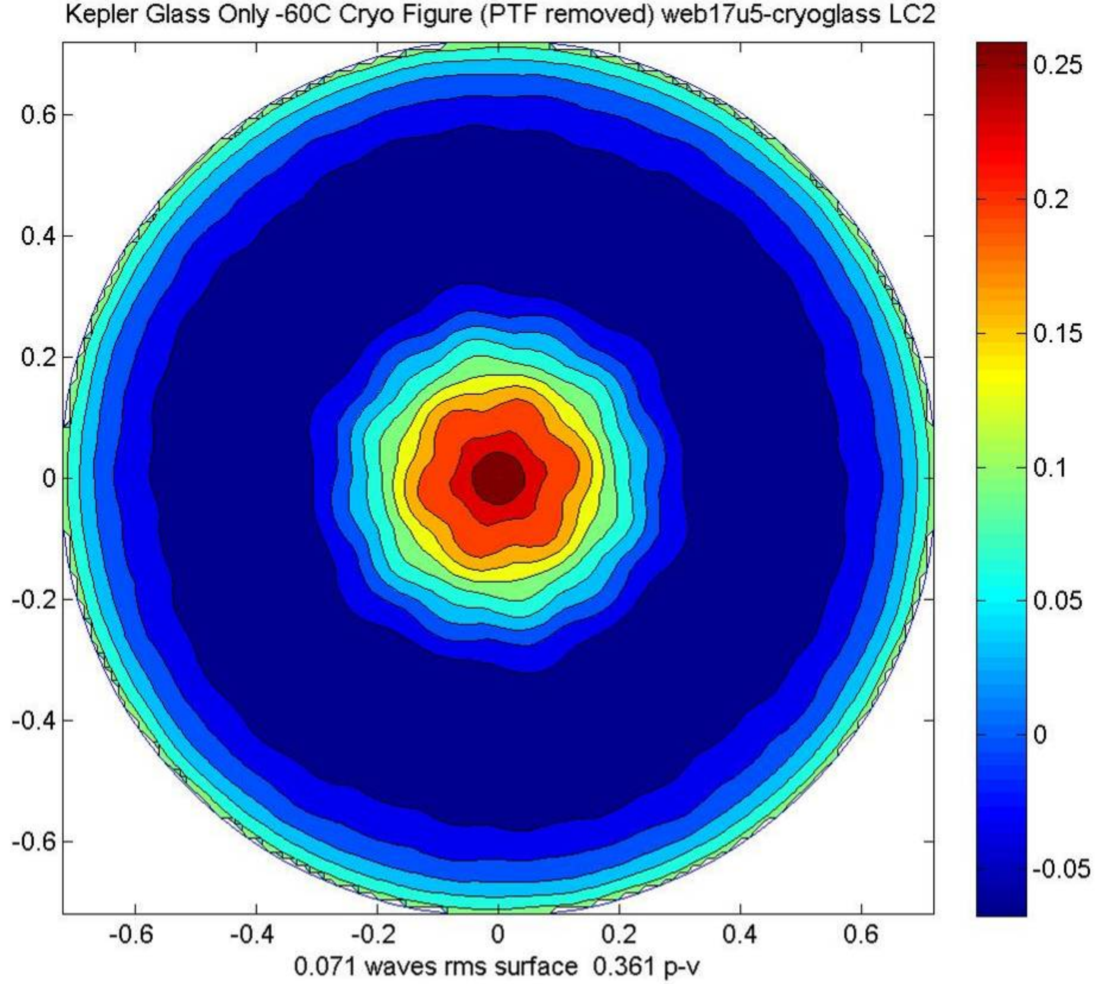
CTE Distribution
on Facesheet

CTE Distribution
on Backsheet





Predicted Cryo Figure Effects at -60°C due to ULE CTE Distribution Only



Material Characterization

Invar Properties - CTE

- Invar CTE in bond pad material is a primary influence on thermal distortion and resulting cryo figure
- Literature and manufacturer reported data show a variety of reported CTE values
- CTE can be reduced with proper heat treatment and aging process
- Also increases based on carbon content in base alloy (furnace impurities)
- Material from final machined flight bond pad tested to give highest accuracy CTE values for final figure prediction

Material Characterization

Adhesive Properties

- Adhesive stiffness and CTE are significant variables in cryo figure prediction
- Adhesive CTE can be easily measured and quantified
- *Stiffness represents biggest unknown*, because it varies widely with temperature, is strain rate dependent, is also dependent on bond thickness, and shows nonlinear stress-strain behavior
- Comprehensive material testing can be used to characterize stiffness, *but challenge is in accurately implementing measured values*
- Actual adhesive thermal effects quantified using an optical test

Material Characterization

Brashear's Optical Measurement of Adhesive Stiffness

- Uniform thickness Invar pad bonded to 6" ∅ glass blank and thermally cycled to -60 °C
- FEA scoping analysis used to determine appropriate thickness of blank such that deflections are large enough to be interferometrically measured without exceeding limits of interferometer
- Cure shrinkage also quantified with this optical test and shown to be minimal due to no observable deformation at room temperature after initial bonding
- Using accurate glass properties, measured Invar properties, and measured adhesive CTE, *the stiffness of the adhesive is varied in the FEA model such that the resulting "power" Zernike term matches the corresponding optical measurement*
- Smaller "spherical" Zernike term not directly correlated but values track with modulus adjustments

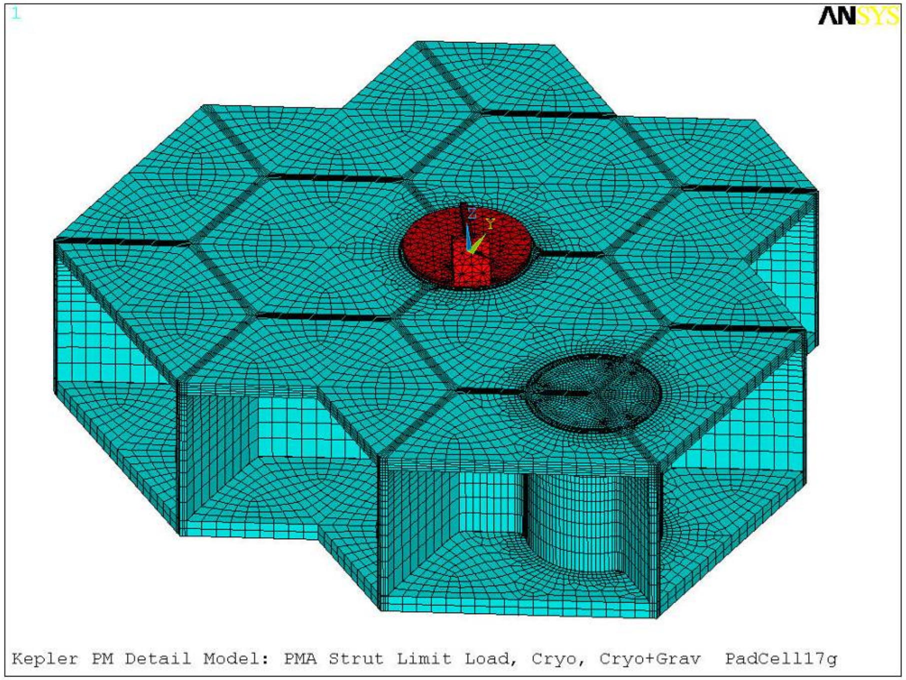
FEA Model Accuracy

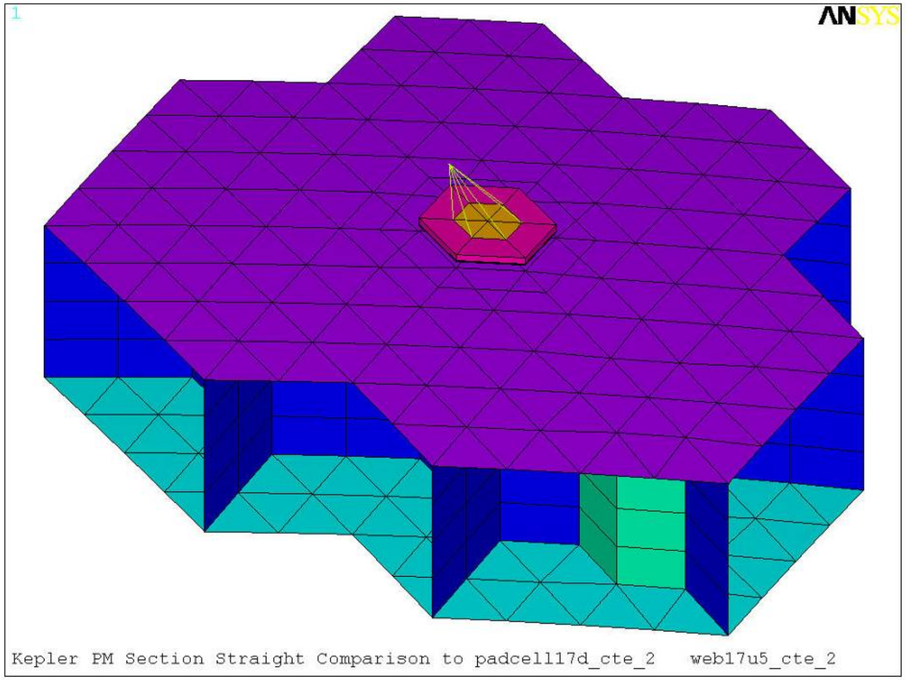
- *Brashear's cost effective approach to FEA* uses two models – one to characterize global effect and another to capture local effects
- Global model has a coarse mesh, with a rough approximation of the adhesive and bond pad geometry
- Unrealistic to build a full PMA model with level of refinement included in the detailed model (cost prohibitive)
- Question - How do you quantify the lower accuracy of the global model in terms of predicting cryo displacements, in order to account for difference?
  - *First, verify accuracy of detailed model which serves as the standard.*

    Mesh refinement of the original detailed model used to demonstrate converged stress results, giving an even higher confidence for displacement predictions.
  - *Second, need to perform results comparison using equivalent models.*

    A section of the global model was generated with similar boundaries and constraints as the detailed model and both were analyzed using the same properties.

Model Comparison





Detailed Model

Global Section Model

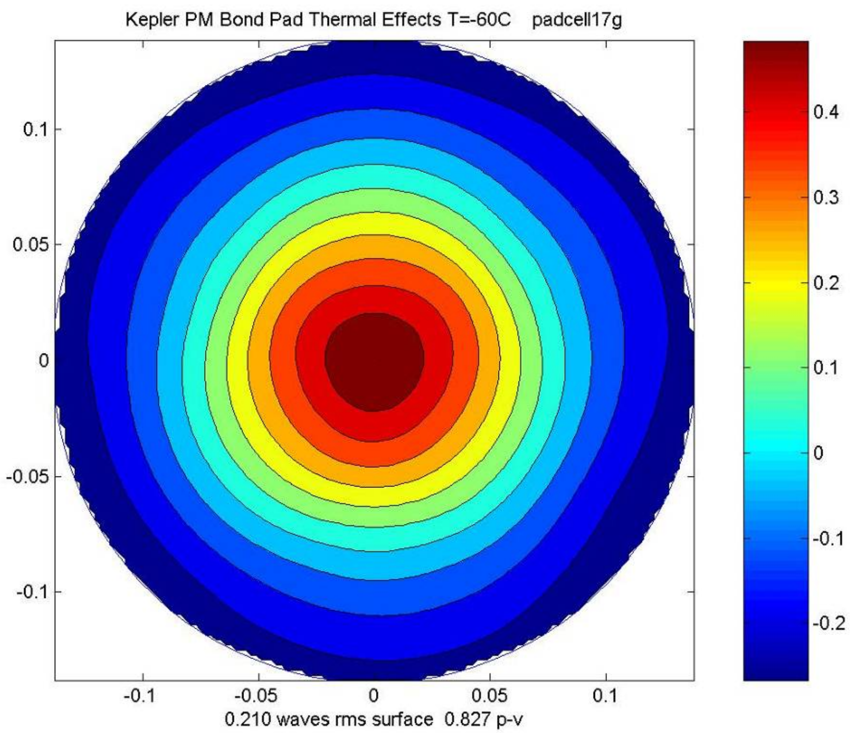
An equivalent section of the global model under-predicts the displacements seen in the detailed model by 37%. Both models use the “correlated adhesive stiffness” obtained earlier.

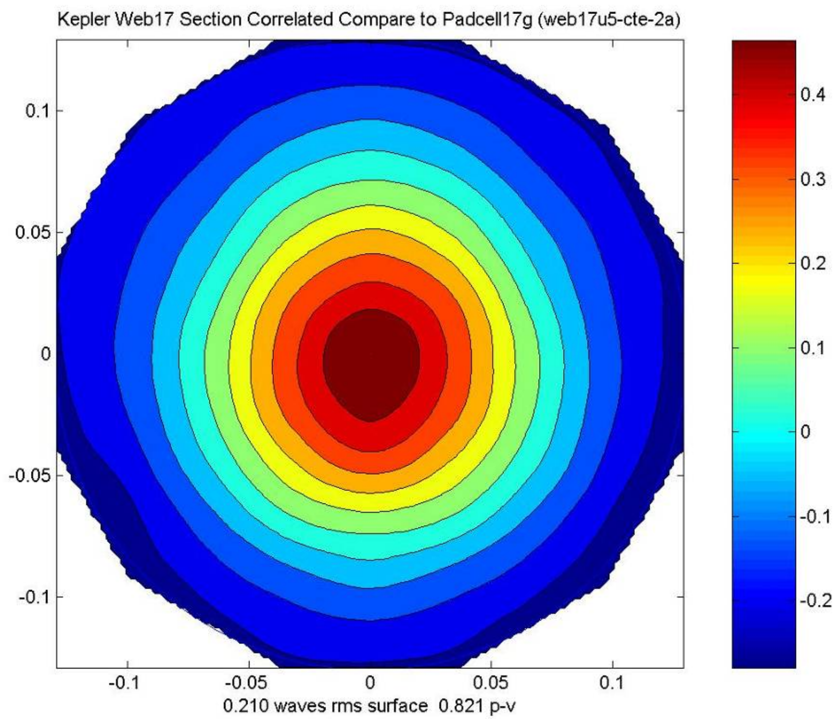
FEA Model Accuracy

How do you adjust the global PMA model to improve its accuracy?

- Cryo displacements driven by (stiffness * CTE) of *both* the adhesive and Invar bond pad
- Chose to increase CTE of Invar to impart the additional force needed in global model to match deflections in detailed model
- Adjusted material properties only used to obtain optical figure from global model. Final stress evaluation obtained using true physical properties in the detailed model.
- Invar CTE is well correlated to cryo displacements – a 50% increase in CTE gives a 30% increase in rms surface figure

Comparison of Local Distortion due to Bond Pad and Adhesive Shrinkage at -60 C





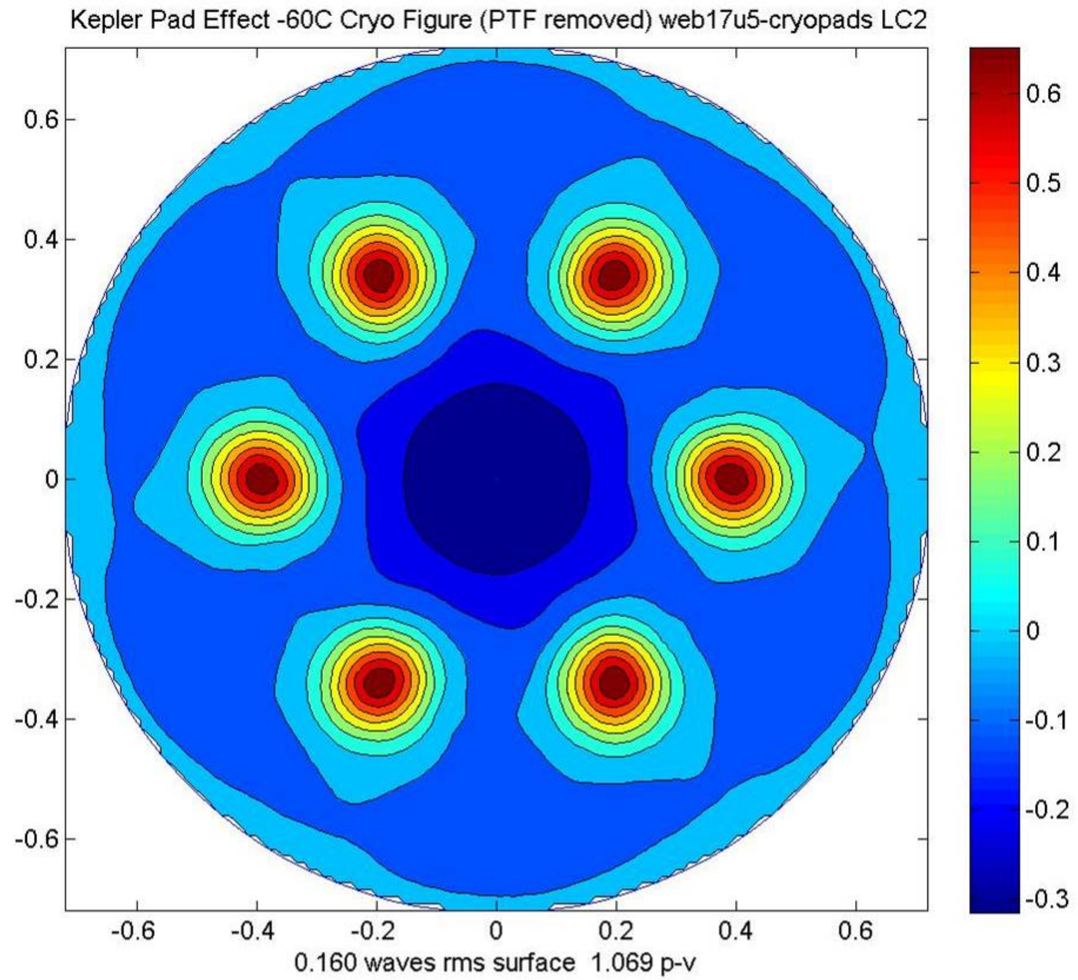
Detailed Model

0.210 waves rms, 0.827 p-v
using true physical material properties

Global Section Model

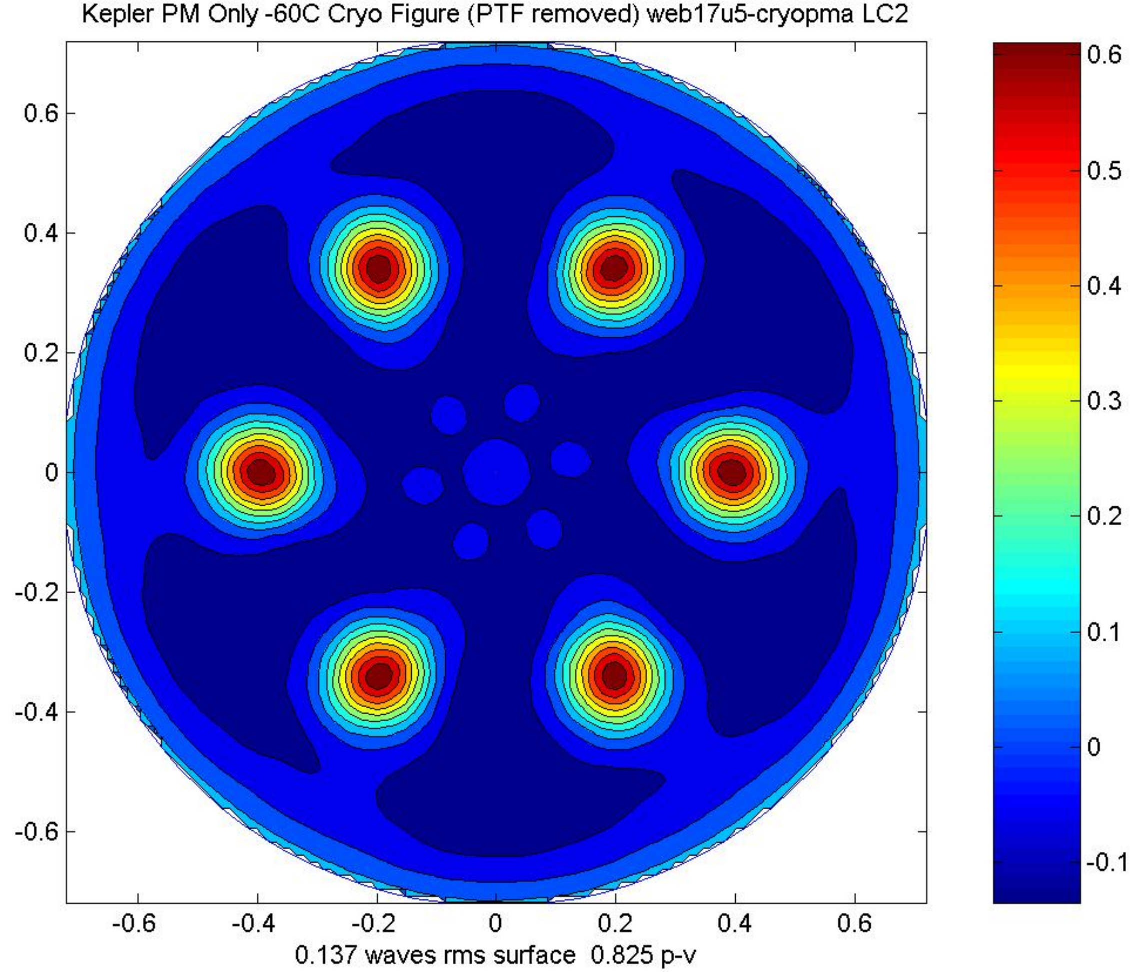
0.210 waves rms, 0.821 p-v
correlated to match detailed model results
using 1.5 factor applied to Invar CTE

Predicted Cryo Figure Effects at -60°C due to Bond Pad and Adhesive CTE Only



This presentation has been reviewed by NASA and determined not to contain technical data as defined by the ITAR Section 120.10.

Final PMA Cryo Figure Prediction at -60°C



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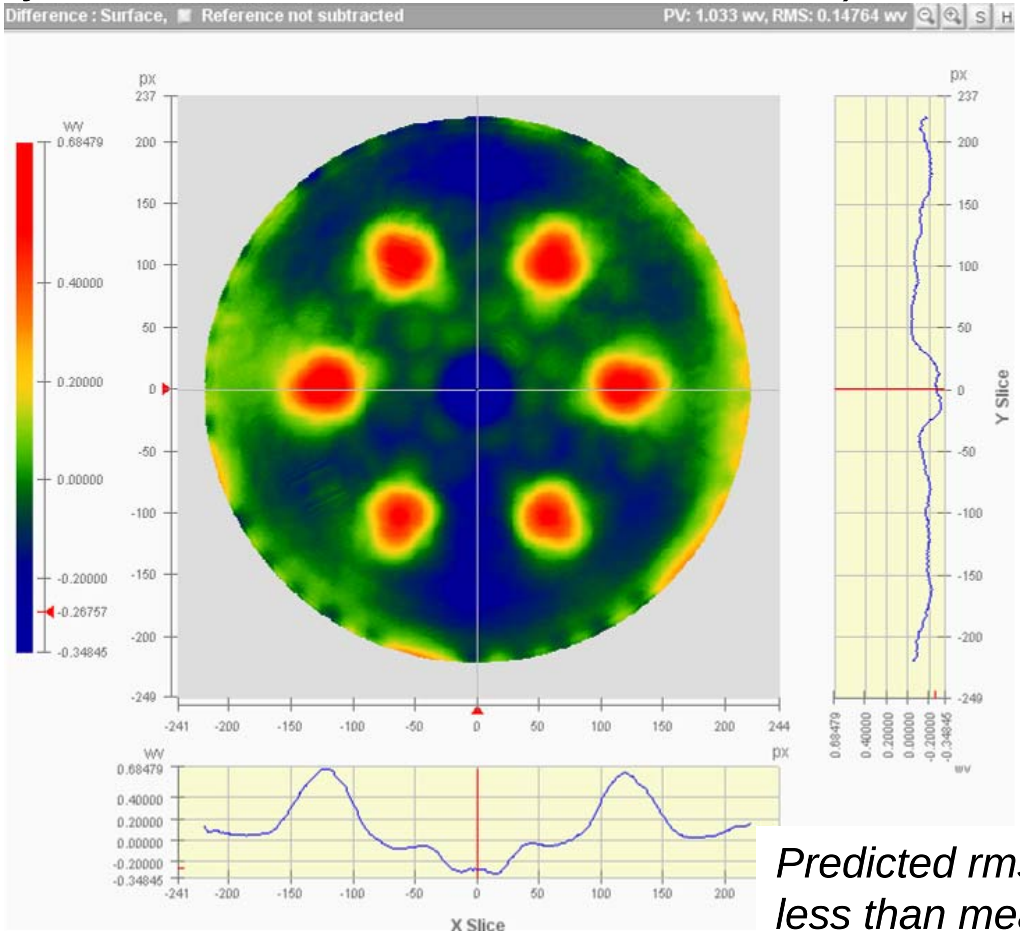
Measured PMA Cryo Figure at -60°C

= (Horizontal Cryo -60 °C – Horizontal Ambient +28 °C) => No Polishing Residual



Predicted rms cryo figure is only 8% less than measured figure at -60 °C.

Source effects are not removed. RMS surface = 0.148 waves.

Closing Remarks

- L-3 Brashear was able to get excellent agreement between measured cryo figure and prediction in a cost effective manner without extremely complex FEA models.
- Magnitude of cryo figure is affected by the bond pad size which was driven by higher launch load requirements earlier in program.
- Original plan was to conservatively cryo null 50% of the predicted error prior to bonding and environmental testing.
- Post-cryo figuring had been planned to account for remaining measured cryo figure but is not needed since the figure meets the system error budget.
- Kepler PMA has successfully completed protoflight level environmental testing, both thermal-vac and vibe, and is currently being coated.